CONTRIBUTION OF GLACIER MELT WATER TO THE FLOW OF THE BOW RIVER

PHASE I (b)

An identification of the contribution (quantity and timing) of release of water from long-term storage as glacier ice to the flow of the Bow River at Banff and to its sub-basins

Final report

by

G J Young,
Wilfrid Laurier University

to

Government of the Province of Alberta
Department of Environmental Protection

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Gordon J Young

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Executive Summary

An overview of the project as a whole

Within the Bow River Basin, Alberta, the demand for water is rising. Already, especially at critical times of the year (late summer) and in years of low flows, demands exceed Alberta's entitlements to water.

Very important questions to be answered at a time when demand is outstripping supply are:

- to what extent is the supply variable over years and decades?
- are long term trends in climate leading to changing stream flows?
- to what extent supplies can be relied upon in the future?

The water supply is derived primarily from the mountain regions in the upper catchment areas where precipitation is relatively high. Much of the mountain precipitation is stored seasonally as snowpacks and over periods of decades and centuries in the form of glaciers. Glaciers provide meltwater primarily in late summer and, in years with relatively low precipitation, glaciers compensate for low flows through additional melting. ***Thus glaciers play a crucial role in water supply for it is precisely when demand is highest that they give their most valuable contributions.***

Over the last few decades glaciers have been in recession, releasing water into the rivers in addition to the annual water budget. This process may well continue and for a number of years there may be a very welcome augmentation of flows. However, as glacier tongues recede to ever higher (and colder) elevations, the contributions of glacier melt to streamflow must, of necessity, diminish. ***It is crucial to the assessment of the available future water resources to understand the quantities and timing of release of glacier ice from long term storage and the rate at which that component of the water supply is likely to change in magnitude.***

It is important to note that the significance of the diminution of glacier extent, with concomitant reduction in water supply, might be completely overshadowed by long term trends in climate, resulting in changes in precipitation quantities or timing of melt periods, or by shorter term but highly significant variations in climate such as a series of years influenced by El Niño events.

While there is a great deal of uncertainty regarding climatic variation over both short and long term time scales, it is possible (at least approximately) to quantify the volume of ice being released from storage over periods of decades and thus to identify the significance of this component of streamflow.

It is the purpose of this research to identify the contribution of glacier ice melt to streamflow, and the changes in that component of the water balance through time in the past and into the future. The geographic extent of the analyses is confined to the catchment of the Bow River above Banff, a catchment within which there has been minimal human influence.

The research has been broken down into three phases:

PHASE I (a) Compilation of data and analysis of trends to the present (already completed)

PHASE I (b) An identification of the contribution (quantity and timing) of release of water from long-term storage as glacier ice to the flow of the Bow River at Banff and to its sub-basins (the subject of the present Report)

PHASE II Future Scenarios

PHASE III Predictors for annual and seasonal forecasts

Executive Summary Continued

PHASE I (b) An identification of the contribution (quantity and timing) of release of water from long-term storage within glaciers to the flow of the Bow River at Banff and to its sub-basins

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The analyses undertaken:

(a) Reconstruction of the extent of glaciers in the Bow River basin above Banff in 1951 and 1993 by utilizing data from the Canadian Glacier Inventory and from aerial photography. This to be undertaken in detail within the sub-catchment above Hector Lake and extrapolated to other parts of the basin.

(b) Calculation of the volumetric change in the glaciers 1951-1993.

(c) Calculation of the variation from year to year in the volumetric change of glaciers.

(d) Calculation of the contributions of the sub-basins to overall flows within the basin of the Bow River at Banff on an annual basis and on a monthly basis with emphasis on contributions in years of low flows.

Main findings of the investigation:

a) For the period 1952 - 92 on average 2.5% of annual streamflow (Bow above Banff) is derived from glacier wastage. On a monthly basis this percentage rises to 4.6%, 7.5% and 5.0% for July, August and September respectively.
b) The years of lowest annual flows are concentrated in the period after 1970. In the 5 lowest flow years the contribution from glacier wastage ranges from 5.2% to 16.8%. For these same years the contribution during August ranges from 13.3% to 47.4%.
c) For the 5 years with the highest contribution of glacier wastage to total flow the proportions range from 7.8% to 16.8%. It is significant that in 1961, a year of *above* average annual flow, 8.3% of that flow was derived from glacier wastage.
d) 1970 stands out as a truly remarkable year, the year of lowest total flow and highest contribution (by far) from glacier wastage.

While some caution is expressed in accepting the precise figures obtained through the analysis (because of a number of sources of error identified in the text) confidence in the general conclusions is high .

1. Principal elements of the mountain hydrological system and definition of terms

A brief summary of the main elements of hydrology of a mountain catchment such as the Bow River above Banff is given here. The factors affecting mountain streamflow are summarized in Table 1.1.

Precipitation inputs are, clearly, the dominant driving force of the system - in general, the greater the annual precipitation the greater will be the annual runoff. Evaporation losses may be substantial, especially in the low-lying forested areas and on open water surfaces.

The form of precipitation is temperature controlled and is thus elevation dependent. Winter precipitation is almost entirely in the form of snow, while summer precipitation, is typically of mixed form, with freezing levels commonly ranging between 2000 and 2600m elevation. There are usually fairly strong precipitation lapse rates with elevation such that the higher elevations receive far greater specific precipitation inputs. Thus, most of the precipitation input in the Bow basin above Banff is in the form of snow. The distribution of snow, prior to the melt phase is further complicated by the redistribution processes of blowing and avalanching.

As most precipitation falls as snow it is the energy inputs leading to melting which influence the rate and timing of release of meltwaters to the streams. The critical elements of the energy balance influencing melting are the radiation components, the sensible and latent heat components. The short wave radiation component, with its dependence on angle of incidence of sunlight and albedo, and the elevation of the freezing level are of particular significance.

Within the mountain hydrology system (as in other hydrology systems) various lags are introduced, which retard the speedy passage of water through the system. The most significant is the seasonal lag as a result of water being stored in the form of snow during winter and reeased through melt processes during the summer. Shorter term lags result from basin size, storage in lakes and in the ground (ground water lags may be short, or may extend over months or years). Much longer term lags (of decades to centuries) are introduced by glaciers - the 20th century has been characterized in the Rockies by glacier shrinkage and the release of water over and above the annual water budget. While the overall trend this century has been for glacier retreat, the record of glacier mass balance shows a combination of both positive and negative balances. The result is that while river flows have been augmented overall by glacier wastage, in some years water has been withheld by glaciers from streamflow. Glaciers have been beneficial to water managers in their regulatory effect over streamflow.

There can be considerable interannual variation in the combination of the critical elements within the mountain hydrological system:

- winter snow-packs can vary considerably, setting the scene for summer melt quantities;
- the timing of the onset of melt can be quite variable, with conditions for the month of May being highly variable from year to year;
- summer temperatures can vary considerably between years and the incidence of summer snowfalls, so critical to albedo, can be very different one year to another;

- the timing of the onset of winter, often marked by a heavy snowfall usually sometime in September, can vary by several weeks from one year to another.

Thus, the detail of the hydrographs on a daily and monthly basis can be very different between years. It is perhaps surprising, therefore, that mean annual flows at Banff are not more variable. In the 1952 - 90 period the low flow year of 1970 (29.4 $m^3 s^{-1}$) is almost 60% of the high flow year of 1954 (50.9 $m^3 s^{-1}$). The reason for to relatively small interannual variability in means annual flows may be attributed primarily to the presence of glaciers with their regulatory influence on water release.

Factors affecting mountain streamflow		
Derivation of streamflow		
Precipitation	*Vertical lapse rate* leading to considerable increase with elevation. Modifications introduced by blowing snow and avalanches *Freezing level* highly important - winter/summer contrast; variation in freezing level between precip. events in summer	*Snowfall* Snowmelt normally by far the most important source of runoff. *Rainfall* A major source in summer and at lower elevations but overall normally of relatively minor importance
Glacier wastage	Highly variable in contribution, usually positive, but sometimes negative. Most important in late summer. Slow change over decades; significant in the long term.	
Evaporation / sublimation	Varies with season. Effects of forest cover (on evapo-transpiration) and open water (lakes and marshes). Of considerable significance in reducing water available to streams	
Lags in the system	*Basin size* In general the smaller the basin the faster the response.	
	Surface detention Lakes, marshes, vegetated areas all introduce lags on a daily - monthly timescale	
	Groundwater Surficial and bedrock storage both significant on a monthly or annual timescale	
	Glacier ice and perennial snow Not all seasonal snowfall may melt out during the hydrological year - in this case glacier mass balances may be positive and there will be a carry-over into the next year.	
	Englacial storage Meltwater storage in firn zone particularly important for supplementing flows in early winter	

Table 1.1 Factors affecting mountain streamflow

Definition of terms

There is some confusion in literature regarding terminology. The term "glacier melt" is somewhat vague as it can comprise melt from glacier ice, from glacier firn and from the seasonal snowpacks on the glacier. In some of the literature it is not clear whether "glacier melt" includes the melting of snow on the glacier or not. Moreover, "glacier melt" is sometimes used to include waters derived off-glacier, but flowing onto or under the glacier from the surrounding terrain.

To minimise confusion, in this paper "snowmelt" is employed to mean snowmelt anywhere in the basin, whether on or off glacier. Similarly "rainfall" includes all rainfall on or off glacier.

The terms "icemelt" and "firnmelt" are avoided in this paper. Rather the term **Glacier wastage** is used to identify that quantity of water coming out of storage over and above an equilibrium mass balance for the glacier. Glacier wastage is expressed on an annual basis but may be partitioned through the year on a monthly (or shorter term) basis. Positive glacier wastage means additional water for streamflow over that derived from seasonal snowmelt and rainfall. Negative glacier wastage implies water held within the glacier reservoir over and above seasonal equilibrium mass balance. It is important to note that even when glacier wastage is negative, there can be considerable streamflow derived from the melting of glacier ice. Thus in a year of positive glacier mass balance (negative glacier wastage), there may still be significant streamflow from ice melt, especially in the late summer months.

---

2. The Bow River Basin above Banff

Details of the characteristics of the basin of the Bow River above Banff have been given in previous reports. The reader is referred to those reports for greater detail. Figs. 2.1, 2.2 and 2.3 illustrate essential elements of the layout of the basin and Table 2.1 and Fig 2.4 present essential information regarding the basin characteristics.

			Area (km sq)								
BASIN		Mean	Total	Forest	Glacier	Lake	Rock	Forest	**Glacier**	Lake	Rock
		elev. (m)						%	**%**	%	%
Bow River at Banff	BB001	2129	2226.7	1160.1	72.9	15.1	978.7	52.1	**3.3**	0.7	44.0
Lake Louise	BA001	2190	425.6	174.8	45.1	9.0	196.6	41.1	**10.6**	2.1	46.2
Pipestone River	BA002	2281	307.8	119.7	9.8	0.4	177.9	38.9	**3.2**	0.1	57.8
Johnson Creek	BA006	2232	124.2	50.9	0.0	0.3	72.9	41.0	**0.0**	0.3	58.7
Baker Creek	BA007	2269	125.5	40.3	0.1	0.6	84.5	32.2	**0.1**	0.5	67.3
Hector Lake	BA008	2286	281.4	83.8	33.2	9.0	155.4	29.8	**11.8**	3.2	55.2
Forty Mile Creek	BB003	2179	133.4	65.0	0.0	0.1	68.3	48.7	**0.0**	0.1	51.2
Brewster Creek	BB004	2218	107.2	48.7	0.5	0.3	57.7	45.5	**0.5**	0.2	53.8
Redearth Creek	BB005	2201	154.2	94.1	1.7	1.2	57.1	61.1	**1.1**	0.8	37.0
Rest of Basin		1974	849.0	566.5	15.7	3.2	263.7	66.7	**1.8**	0.4	31.1
COMPARATIVE BASINS											
Mistaya River	DA007		247.2	83.8	26.6	5.8	130.9	33.9	**10.8**	2.4	52.9
Silverhorn Creek	DA010		20.0	1.9	0.6	0.0	17.5	9.6	**2.9**	0.0	87.5
Peyto Creek	DA008		22.2	0.0	12.1	0.0	10.1	0.0	**54.5**	0.0	45.5

Table 2.1 Summary of Basin Characteristics

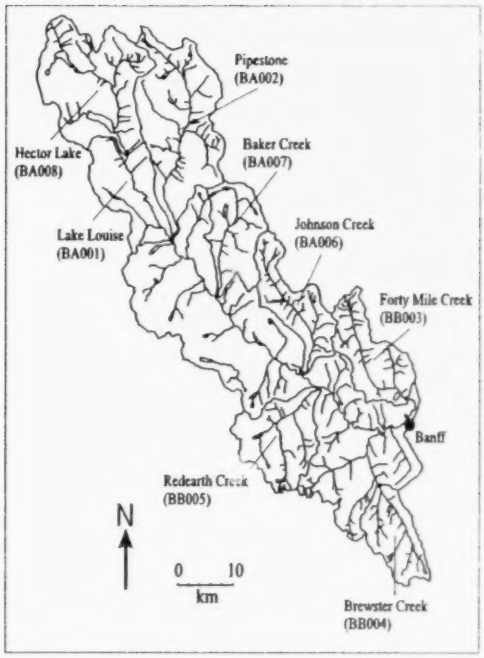


Fig 2.1 Sub-basin delimitation and glaciers

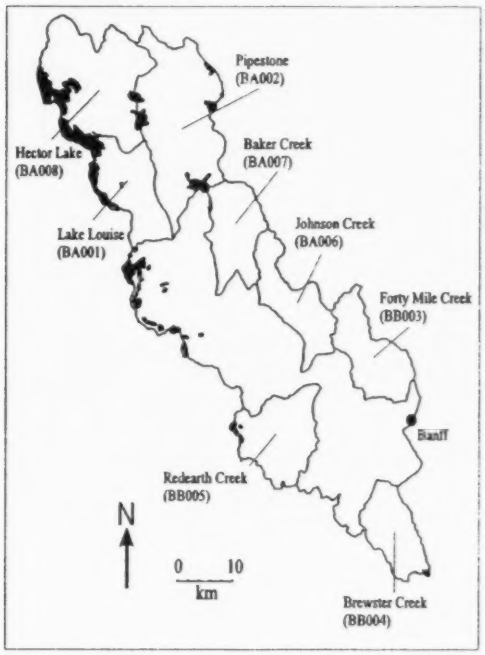


Fig 2.2 Stream network

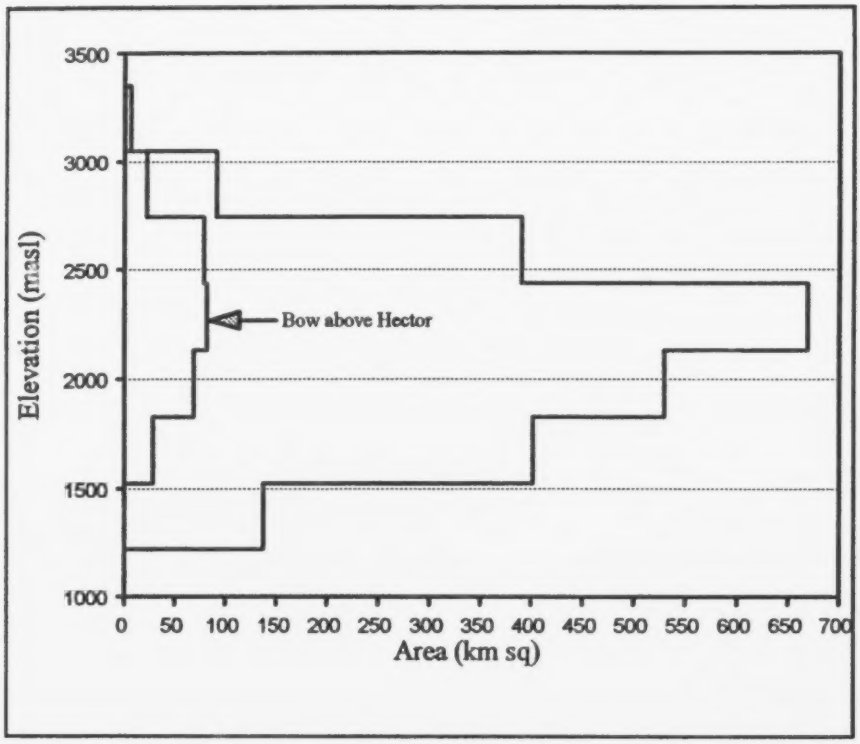


Fig 2.3 Hypsographic curve Bow above Banff with Hector Lake superimposed

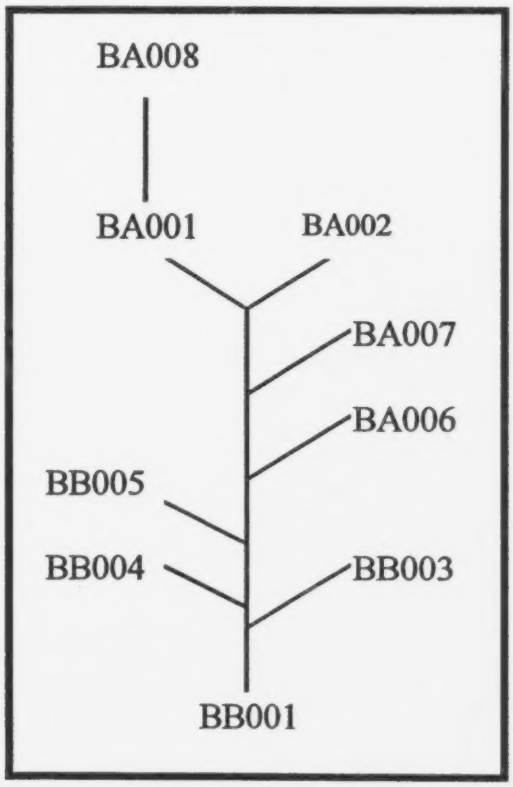


Fig 2.4 Stream network schematic

3. The data records

Essential records have been illustrated in the previous data report and the reader is referred to these for more detail. (Particular attention is drawn to Figs 2.2 through 2.8 for discharge records).

Fig 3.1 illustrates mean annual flows at Banff 1911-92 with the record for 52-92 highlighted (the period for which detailed analyses have been undertaken for this study). The period 73-76 has been particularly identified as the period when many measurements were taken on streams throughout the basin, including Hector Creek. Flows up to 1969 were, in general, higher than the period 1970 - 92, although after 1970 there were often distinct differences in flows from one year to the next.

Fig 3.2 shows the detailed hydrograph, of daily flows, for the years 1973 - 76; not only are total quantities variable, but peak discharges and the seasonal regimes show considerable variability.

Fig 3.3 illustrates monthly variance in flows for 1973 - 76, in comparison to the 82 year monthly means. June shows considerably higher variance than either July or August.

Fig 3.4 shows specific mean monthly yields for the highly glacier-covered Hector sub-catchment in comparison to the unglacierized Forty Mile Creek. Winter flows are unavailable. It is readily apparent that the yield from the glacierized catchment is far higher, especially in late summer. The yields for the total Bow catchment are midway between the extreme yields of the sub-catchments.

Fig 6.2 shows the Peyto Glacier measured mass balance records 1966 - 90 (winter, summer and net annual balances).

The period 1966-90 may be divided into two fairly distinct segments 1966-76 and 1977-90. In the first period was one of relatively high winter balances with a mixture of positive and negative net annual balances. The period 1977-90 was characterized by a series of relatively low winter balances and, without exception, a series of negative net annual mass balances.

It is important to note that glacier mass balances have, each year been given relative to the glacier extent in that year. The glacier has been diminishing in extent, and retreating to higher mean elevations throughout the twentieth century. Thus we should really be comparing the specific mass balance at the same elevation (or elevations) through time. This has not been done and leads to some inaccuracies in results of analyses.

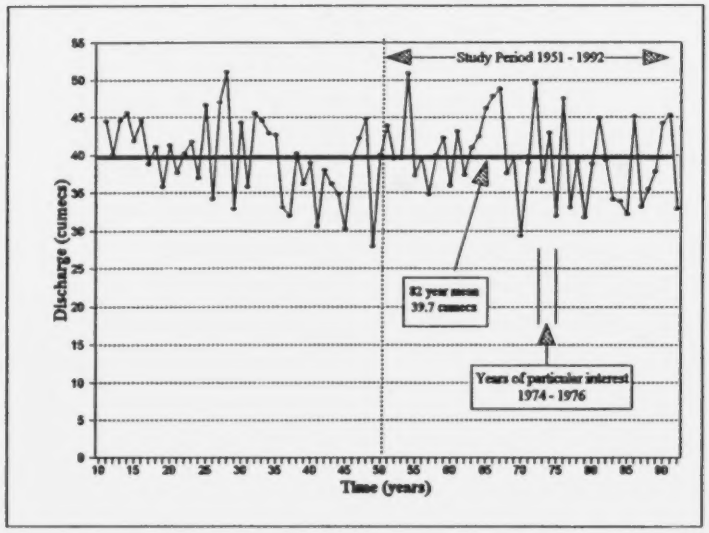


Fig 3.1 Mean annual flows Bow River at Banff 1910 - 92

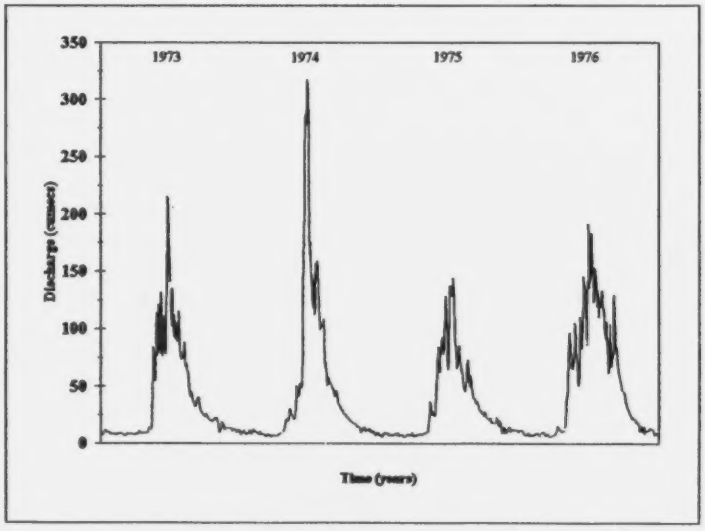


Fig 3.2 Daily flows Bow River at Banff 1973 - 76

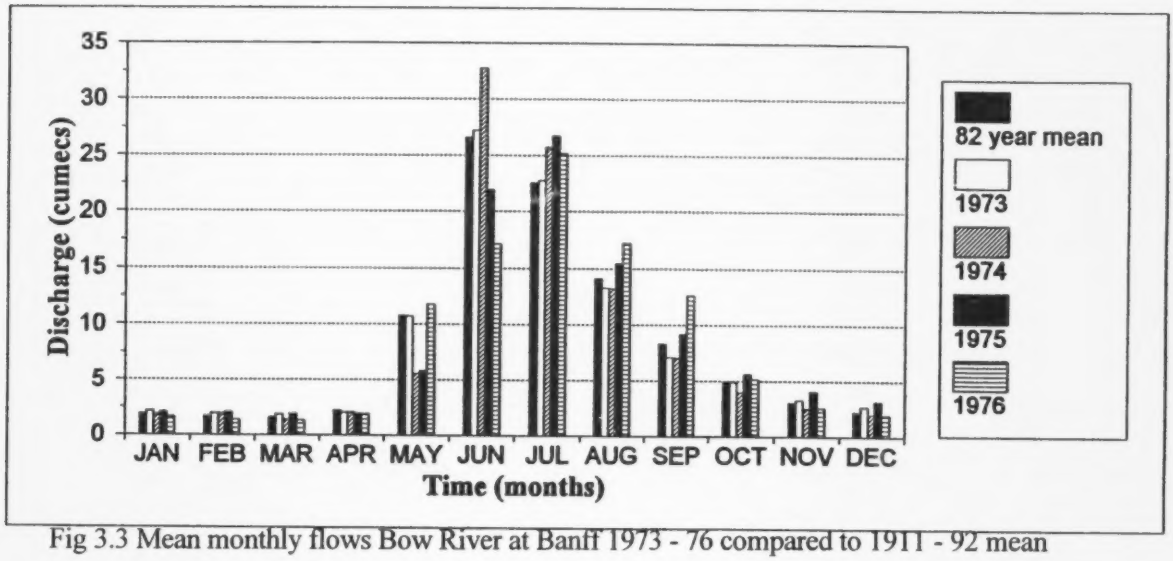


Fig 3.3 Mean monthly flows Bow River at Banff 1973 - 76 compared to 1911 - 92 mean

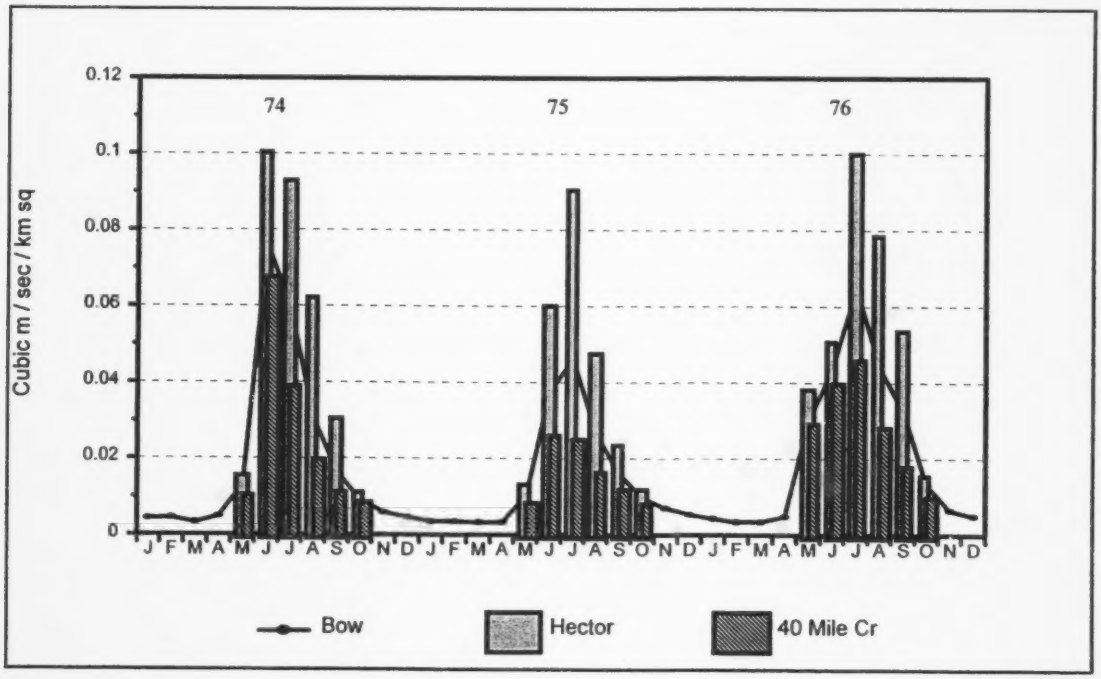


Fig 3.4 Specific mean monthly yield 1974 - 76 Bow River at Banff and two sub-catchments

4. A summary of the investigative method

1. Calculate glacier volumetric loss 1951-1993 in the Hector Lake Sub-catchment;
   (a) From the 1951 and 1993 air photos, trace the extent of all glaciers onto the 1:50 000 topographical map;
   (b) Calculate areas for 1951 and 1993 using "MapInfo" software;
   (c) Superimpose 100m contours by interpolation from 1:50 000 map;
   (d) Create a hypsographic curve for glacier areas by summation of areas within each elevation band;
   (f) Estimate vertical lowering for each elevation band by applying the lowering rates experienced on Peyto Glacier for the period 1966-89;
   (g) Calculate the volumetric loss for the entire 1951-93 period for each elevation band; and sum for all bands to arrive at total volumetric loss.

2. Calculate the volumetric loss for the basin of the Bow above Banff by applying a scaling factor of 2.19 (the Hector basin containing about 45% of the total glacierized area).

3. Calculate average annual volumetric for the years between the aerial surveys.

4. Calculate actual annual volumetric loss by applying the measured net annual mass balance record from Peyto Glacier (back-casted from 1966 to 1951).

5. Apportion the annual losses (in the case of gains this was not applied) through the 4 summer months in the proportions: June 10%; July 35%; August 40%; September 15%.

5. Glacier recession within the Hector Sub-basin

Air photos of the Hector Lake sub-catchment were examined for 1951 and 1993. Plate 5.1 shows that part of the mosaic of aerial photographs for the glaciers immediately above Hector Lake. Plate 5.2 illustrates roughly the same region as seen from the ground for 1904 and 1996. These plates illustrate dramatically the marked glacier retreat during these periods.

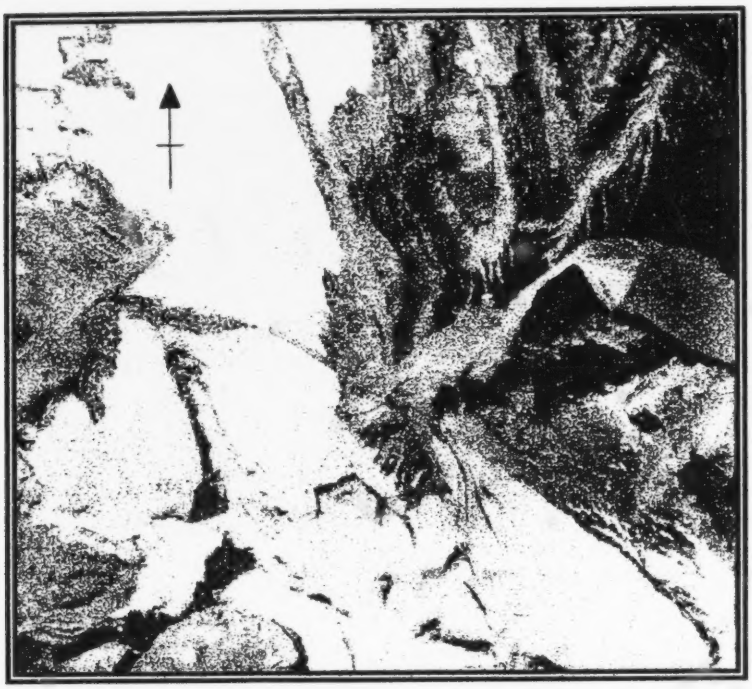
The glacier extents for each year were traced onto the 1:50 000 scale topographic map and overlaid to produce fig 5.1. "MapInfo" software was used to calculate glacier areas for each time period.

100m contours, interpolated from the imperial 100ft contours on the 1:50 000 map were traced over the glacier outlines to define elevation bands; these are shown in figs 5.2 and 5.3. It should be noted that there is considerable possible inaccuracy in the position of the contours, from the topographic map, generated from aerial photography around 1950. As the glaciers receded, so the contours would have migrated with glacier wastage; however, in this analysis the position of the contours remained unchanged. Thus another error would have been introduced here. However, it is considered likely to be very small.

A summary of change in total extent of glaciers within 100m elevation bands is shown in fig 5.4. A detailed summary by elevation band for each glacier is given in table 5.1.

An estimation was then made of vertical melt for each elevation band during the 42 year period. The rate of surface lowering on Peyto Glacier for the period 1966 - 89 was extrapolated forwards to 1993 and backwards to 1952 and then used as the model for melt rates within each elevation band for the Hector Lake catchment. It is, of course, a best guess that the melt rates on Peyto Glacier are representative for the entire Hector Lake catchment. It is also questionable whether the extrapolations backwards and forwards are legitimate; however our best estimates are that it is reasonable to make such assumptions.

Volumes of ice loss in each elevation band were made assuming a trapezoidal cross-section; ie the areas near the edges of the glaciers would have experienced less volumetric loss due to shallow depths of ice in those areas and the fact that the ice melted out completely within the 42 year period of study. Total water losses were then calculated by applying a conversion factor of 0.85. While ice density is usually taken as 0.91, the 0.85 multiplier was thought more applicable to take account of voids in crevassed areas and within those parts of the firn regions experiencing losses. Table 5.2 summarizes glacier volumetric loss by elevation band. Water losses were then summed for all elevation bands and divided by 42, the number of years within the study period, to give an average annual figure. The figure for the Hector catchment corresponds very closely to the losses calculated for the Mistaya catchment for the period 1966 - 89.



Waputik Mountain glaciers, Hector Basin 1951

Plate 5.1 Waputik Mountain glaciers, Hector Basin 1993

Balfour Glacier & Wapta Icefield, Hector Lake Basin 1904

Balfour Glacier & Wapta Icefield, Hector Lake Basin 1996

Plate 5.2

Hector Lake Basin with Glacier Extents for 1951 and 1993

Glacier extent 1951

Glacier extent 1993

★ Hector Lake Basin gauge on Bow River

1 - 21 Glacier identification numbers according to the Waputik Mountain Glacier Inventory (Stanley, 1970)

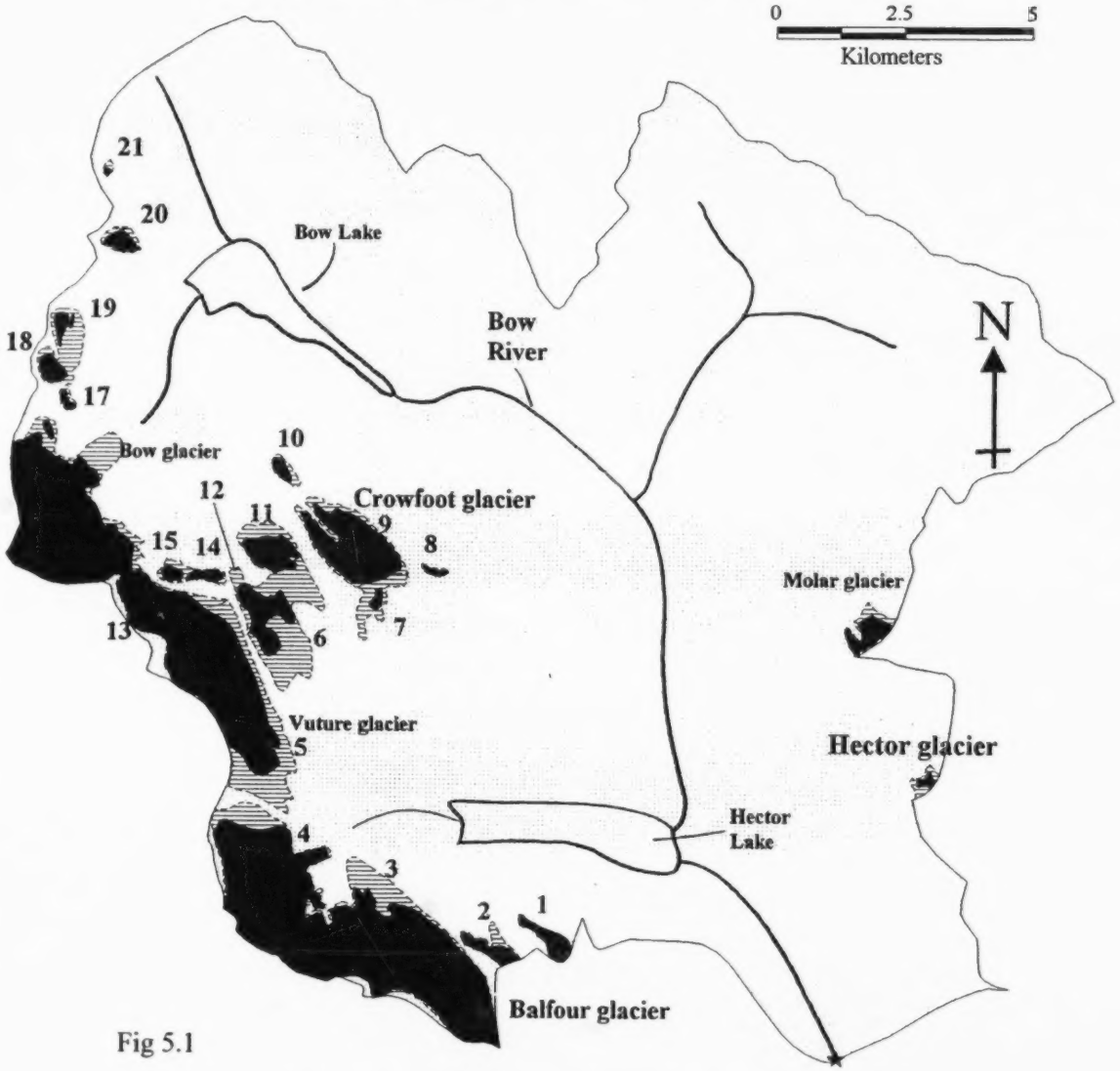


Fig 5.1

Hector Lake Basin with Glacier Elevation Bands for 1952

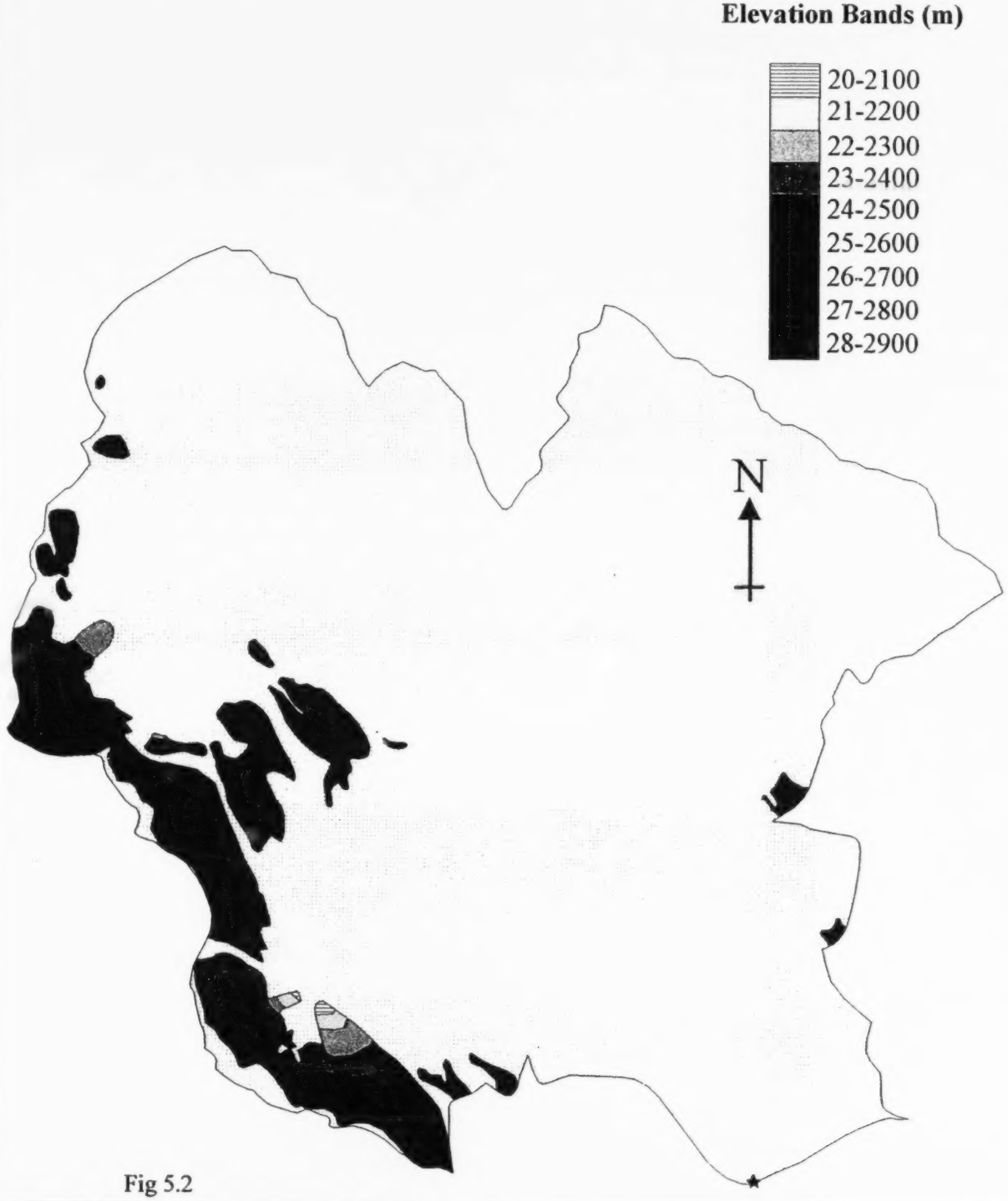


Fig 5.2

Hector Lake Basin with Glacier Elevation Bands for 1993

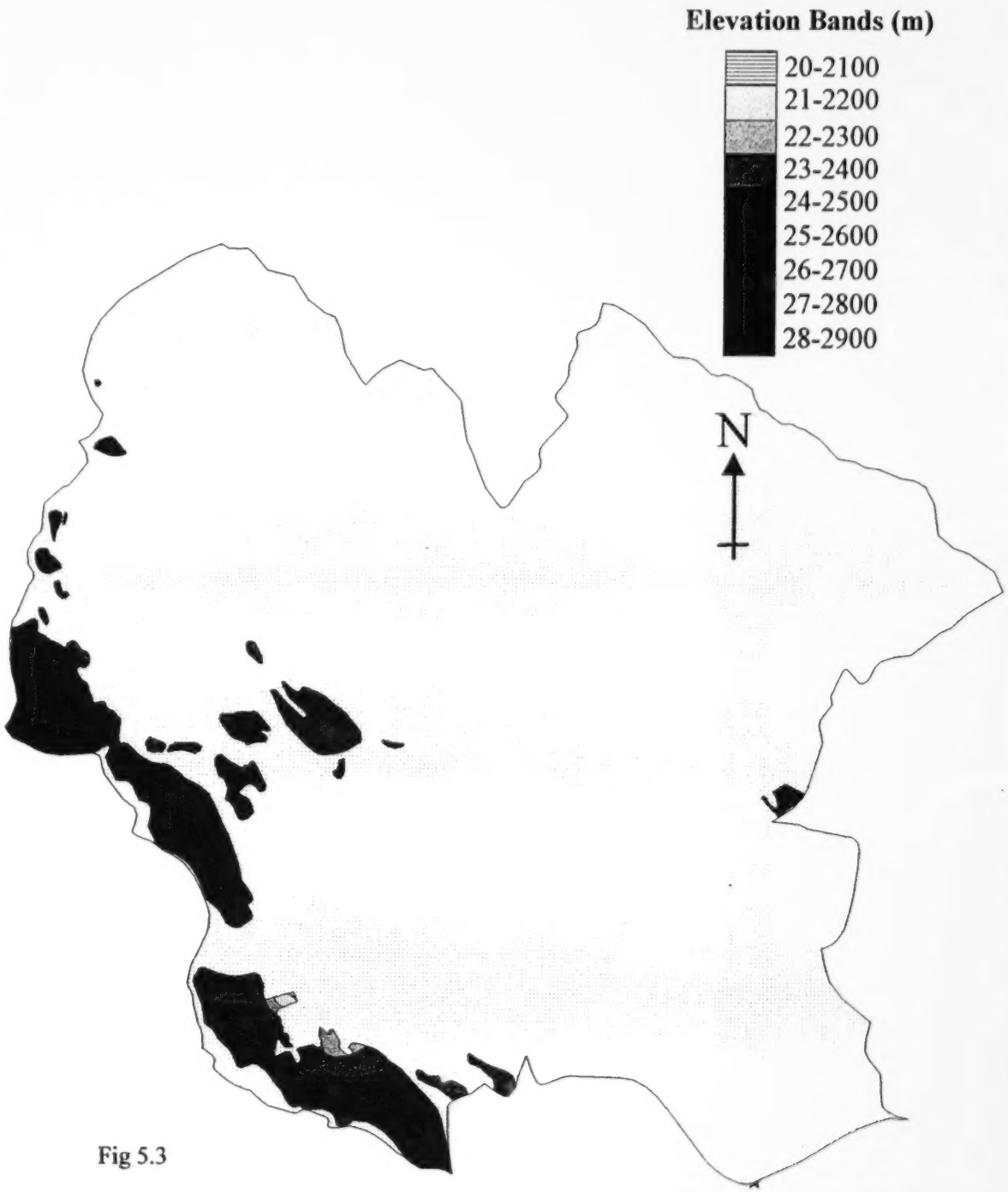


Fig 5.3

Hypsographic Curve of Glacier Extents for Hector Lake Basin, 1951 & 1993

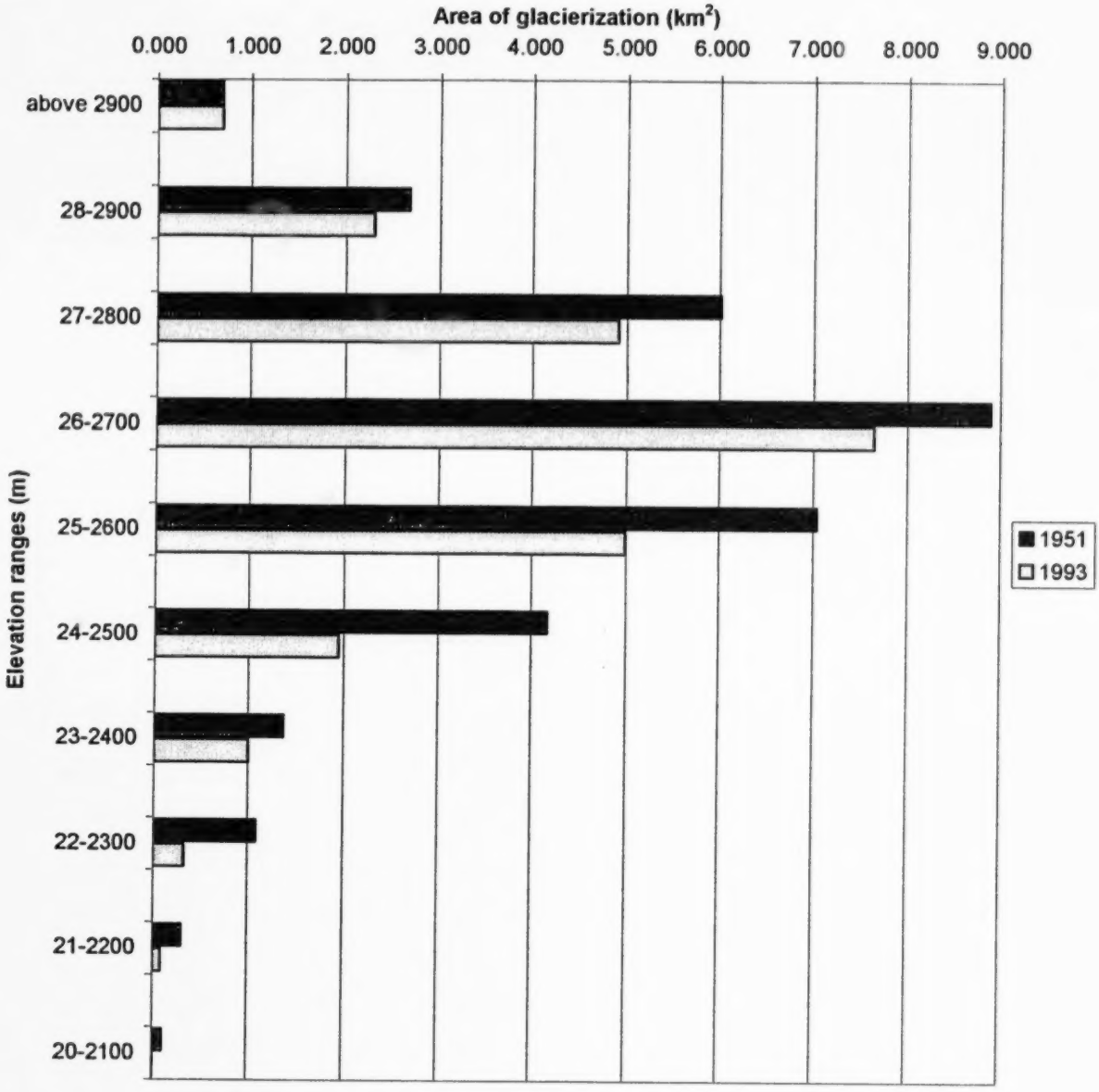


Fig 5.4

Hypsographic Curve of glacier areal extents for Hector Basin (276 km^2) 1951 and 1993. (Ranges subject to ice melt only)														
Elevation		Glacier name or number according to 1967 inventory (stanley)												
Range (m)	Year	Molar	Hector	1	2	3	4	5	6	7	8	9	10	
28-2900	1951	0.064	0.055	0.009		0.255	0.448	0.750	0.140	0.073		0.102		
	1993	0.051	0.009	0.009		0.430	0.439	0.616	0.023	0.000		0.063		
27-2800	1951	0.100	0.098	0.049		1.234	0.452	1.331	0.621	0.109		0.619		
	1993	0.085	0.053	0.049		1.167	0.439	1.228	0.150	0.017		0.548		
26-2700	1951	0.235	0.013	0.090	0.057	1.196	0.603	1.033	0.699	0.185		0.683		
	1993	0.158		0.090	0.057	1.172	0.567	0.940	0.500	0.053		0.622		
25-2600	1951	0.047		0.160	0.249	1.139	0.814	1.273	0.787	0.150	0.066	0.309	0.086	
	1993			0.160	0.208	1.125	0.776	0.945	0.140	0.015	0.045	0.262	0.038	
24-2500	1951			0.029	0.053	0.888	0.792	0.708	0.170			0.235	0.088	
	1993			0.029	0.000	0.854	0.396	0.105				0.171	0.062	
23-2400	1951				0.029	0.780	0.221	0.094				0.080		
	1993					0.712	0.176							
22-2300	1951					0.582	0.073							
	1993					0.264	0.067							
21-2200	1951					0.205	0.101							
	1993					0.000	0.091							
20-2100	1951					0.094	0.022							
	1993						0.009							
Total area	**1951**	**0.497**	**0.172**	**0.329**	**0.387**	**6.940**	**4.200**	**5.280**	**2.420**	**0.502**	**0.066**	**2.030**	**0.174**	
of each	**1993**	**0.345**	**0.062**	**0.316**	**0.261**	**6.070**	**3.630**	**3.880**	**0.773**	**0.085**	**0.045**	**1.660**	**0.100**	
glacier														
Range (m)	Year	11	12	13	14	15	16	17	18	19	20	21	**Total area**	
													for each range	
28-2900	1951	0.099		0.672					0.022				**1.895**	
	1993	0.071		0.589					0.013				**1.640**	
27-2800	1951	0.423	0.045	0.583			0.204		0.155				**4.612**	
	1993	0.329	0.027	0.528			0.199		0.094				**3.735**	
26-2700	1951	0.223	0.047	0.797			2.585		0.079	0.298	0.079		**4.794**	
	1993	0.119	0.000	0.749			2.369		0.073	0.135	0.048		**4.158**	
25-2600	1951	0.053	0.024	0.342	0.061		0.765	0.103	0.098	0.300	0.197	0.026	**5.080**	
	1993			0.242	0.033		0.757	0.061	0.037		0.145	0.016	**3.713**	
24-2500	1951			0.031	0.100	0.812	0.233				0.017	0.019	**2.964**	
	1993				0.089	0.031	0.215						**1.617**	
23-2400	1951					0.118	0.066						**1.203**	
	1993					0.072	0.053						**0.887**	
22-2300	1951					0.023	0.423						**0.655**	
	1993												**0.331**	
21-2200	1951												**0.307**	
	1993												**0.091**	
20-2100	1951												**0.116**	
	1993												**0.009**	
														Basin
														cover (%)
Total area	**1951**	**0.795**	**0.114**	**2.500**	**0.200**	**0.182**	**4.260**	**0.103**	**0.500**	**0.448**	**0.292**	**0.045**	**22.997**	**11.7**
of each	**1993**	**0.515**	**0.026**	**2.150**	**0.123**	**0.102**	**3.570**	**0.061**	**0.217**	**0.135**	**0.190**	**0.016**	**16.882**	**8.7**
glacier														

Table 5.1

Elevation range (m)	Area (km^2) 1951	Area (km^2) 1993	Depth of glacier surface melt (m)	Glacier volume loss ($m^3 \times 10^6$ w.e.)
<2900	0.700	0.700	0.0	0.0
28-2900	2.688	2.312	9.1	19.3
27-2800	6.020	4.913	13.7	63.7
26-2700	8.902	7.650	16.1	113.3
25-2600	7.048	5.002	28.1	143.9
24-2500	4.175	1.951	38.5	100.2
23-2400	1.387	1.013	78.2	79.8
22-2300	1.100	0.331	101.2	61.5
21-2200	0.307	0.091	45.7	7.7
20-2100	0.116	0.009	18.3	1.0
Total catchment glacier wastage 1951 - 93 = 590.4 $m^3 \times 10^6$ w.e. (14.1 $m^3 \times 10^6$ w.e. per year)				

Table 5.2 Summary of glacier loss by elevation for Hector Lake catchment

6. Calculation of glacier wastage contribution to the flows of the Bow River above Banff

Extrapolation of glacier wastage within the Hector Lake sub-catchment to the Bow above Banff.

The Hector Lake sub-catchment contains about 45% of the total glacier area within the entire basin. It is assumed that the glaciers within the sub-catchment are representative of the total population of glaciers in mean slope and aspect, in elevation range etc. Thus the figures calculated for total glacier wastage within the Hector Lake sub-catchment were simply multiplied by 2.19 to arrive at total net glacier volumetric loss of 1292.98 $m^3 \times 10^6$ (w.e.) over the 42 year period.

Calculation of actual annual water losses.

A distribution of the total catchment losses for each of the 42 years of record was arrived at by assuming that the glacier mass balance figures within the region would be the best indicator of glacier water storage change. Years of negative mass balance would correspond to years of water loss and *vice versa*. The magnitude of the glacier mass balance (either negative or positive) would reflect the magnitude of catchment water loss or increased storage. No glacier mass balance records exist within the catchment of the Bow above Banff, but excellent records have been maintained on the Peyto Glacier (in the adjacent Mistaya catchment) from 1966 to the present by the National Hydrology Research Institute. (These records have been kindly made available to us by Mr Mike Demuth). Knowing that net annual mass balance correlates fairly well with mean minimum May to July temperature records for Jasper townsite, net annual mass balance for Peyto Glacier has been estimated for the years 1951 - 66. The annual weighting of annual losses (or gains) due to glacier wastage was derived from multiplying the total water loss by the net balance figure for the corresponding year and then dividing by the net balance for the entire 42 year period.

Monthly weighting of catchment water losses.

From the detailed hydrological studies undertaken in the Peyto Glacier catchment it has been concluded that virtually all glacier wastage occurs within the period June through September. From the studies undertaken on the hydrograph records of 1967 - 74 it has been concluded that the mean proportions of wastage for June, July, August and September were 10%, 35%, 40% and 15% respectively. These proportions have been applied to all years of record. Clearly errors are introduced with this assumption and a more realistic apportionment should be attempted in future calculations. However, while changing the detailed apportionment within the summer season, it is argued that the total annual wastage is the more important figure. By applying the same monthly apportionment from year to year, our estimates of monthly contributions may well be conservative in some critically low flow years. For years of positive mass balance and hence increase in glacier dimensions, we have not made estimates of monthly contribution of glacier "wastage".

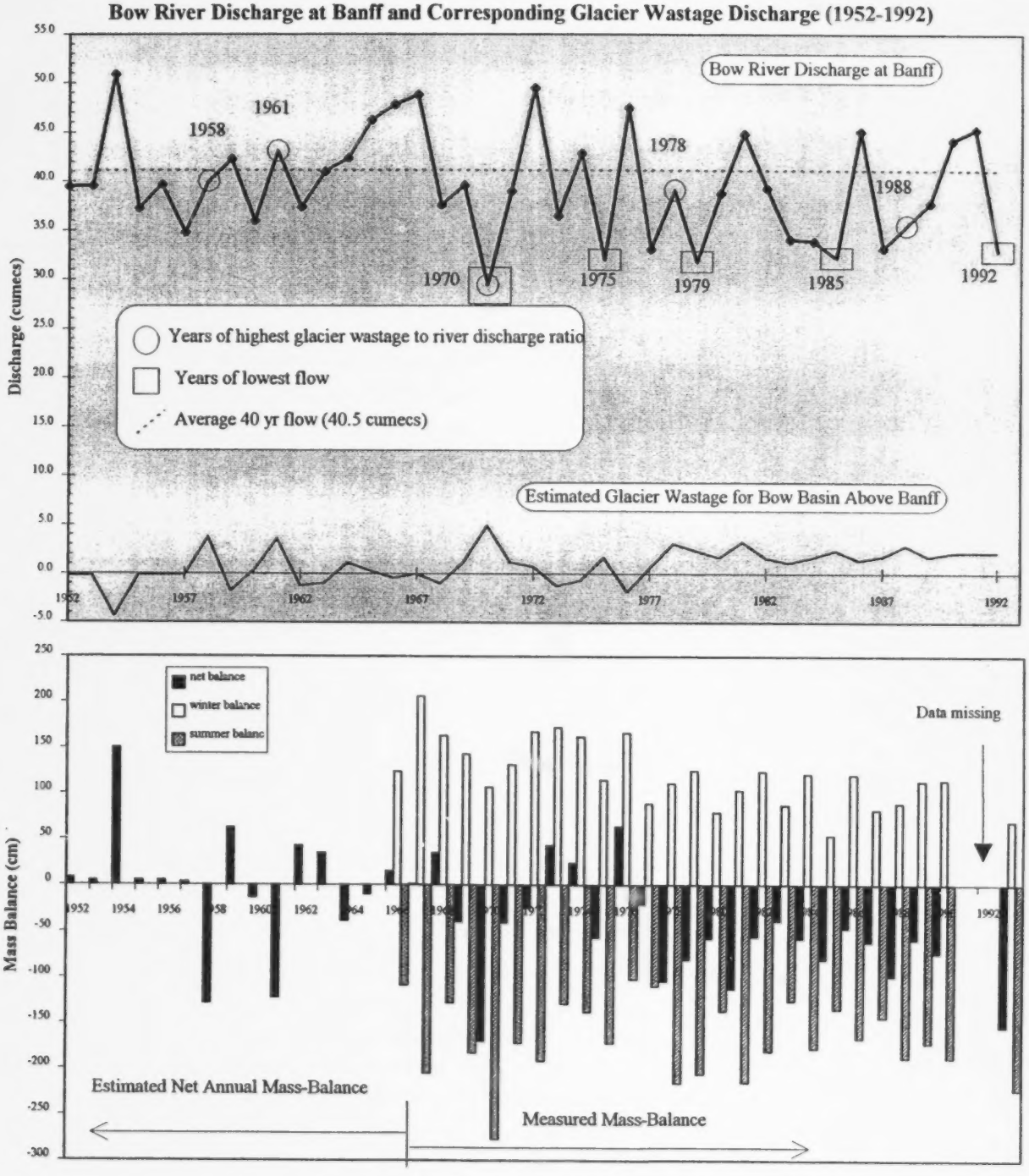
Summaries of critical findings are presented in table and figure form, below. Table 6.1 shows a listing and accounting for annual flows for the period 1952 - 90. The years of low flow are highlighted and are seen to cluster in the later years of record. The months within the record when

the proportion of glacier wastage to total flows is above 15% are also indicated. Mean annual flows and corresponding discharge derived from glacier wastage are shown in fig 6.1. Fig 6.2 shows the corresponding mass balance for Peyto Glacier. Critical years have been selected for more detailed examination within table 6.2. It is significant that, while the mean annual contribution of glacier wastage to total flows is 2.4%, in the 5 years of lowest flows glacier wastage contribution is far higher. It is also significant that in some years with above or near average total annual flows (1961 and 1958) the contribution of glacier wastage can be high (8.3% and 9.4% respectively). Table 6.2 and fig 6.3 show that glacier wastage contributions to flows within particular months, especially August, can be very high. (Again, it should be noted that some of these estimations may, in fact, be conservative). It is readily apparent that, should the glaciers continue to recede, these significant contributions to flow must, of necessity, eventually diminish.

Table 6.1 Summary of annual and summer flows with glacier wastage contribution 1952 - 90

Bow River Basin Above Banff																
Estimated Annual glacier loss			Monthly (m^3s^{-1})				Measured Discharge (m^3s^{-1})					Glacier wastage / discharge (%)				
Year	(m^3x10^6we)	(m^3s^{-1})	June	July	August	Sept	Annual	June	July	August	Sept	Annual	June	July	August	Sept
1952	-7.45	-0.2					39.5	117.0	105.0	67.6	32.0	-0.6				
1953	-4.66	-0.1					39.6	128.0	119.0	64.3	38.4	-0.4				
1954	-137.32	-4.4					50.9	130.0	184.0	96.2	60.1	-8.6				
1955	-4.35	-0.1					37.3	128.0	122.0	60.3	35.3	-0.4				
1956	-4.77	-0.2					39.7	149.0	97.3	54.6	27.2	-0.4				
1957	-3.23	-0.1					34.8	101.0	70.2	46.8	29.7	-0.3				
1958	118.04	3.7	4.4	*15.9*	*17.6*	6.6	40.0	121.0	95.3	60.3	33.8	9.4	3.6	**16.7**	**29.2**	**19.6**
1959	-57.27	-1.8					42.3	143.0	118.0	59.5	49.2	-4.3				
1960	12.85	0.4	0.5	1.7	1.9	0.7	36.0	102.0	121.0	57.0	35.5	1.1	0.5	1.4	3.4	2.0
1961	112.71	3.6	4.2	*15.2*	*16.8*	6.3	43.1	177.0	83.0	67.6	31.2	8.3	2.4	**18.3**	**24.9**	**20.2**
1962	-39.21	-1.2					37.4	114.0	104.0	68.4	35.5	-3.3				
1963	-31.69	-1.0					41.0	132.0	109.0	67.5	45.9	-2.5				
1964	35.77	1.1	1.3	4.8	5.3	2.0	42.4	155.0	129.0	59.1	37.5	2.7	0.9	3.7	9.0	5.3
1965	9.33	0.3	0.3	1.3	1.4	0.5	46.2	154.0	134.0	83.4	39.1	0.6	0.2	0.9	1.7	1.3
1966	-13.76	-0.4					47.8	142.0	141.0	73.0	41.6	-0.9				
1967	-0.92	0.0					48.8	208.0	139.0	74.1	46.0	-0.1				
1968	-32.12	-1.0					37.6	127.0	110.0	58.8	37.9	-2.7				
1969	36.71	1.2	1.4	5.0	5.5	2.1	39.6	134.0	91.7	59.1	34.9	2.9	1.0	5.4	9.3	5.9
1970	156.00	4.9	5.8	*21.1*	*23.3*	8.7	29.4	110.0	74.5	49.1	24.9	16.8	5.3	**28.3**	**47.4**	**35.1**
1971	37.62	1.2	1.4	5.1	5.6	2.1	39.0	137.0	91.7	70.9	33.8	3.1	1.0	5.5	7.9	6.2
1972	22.94	0.7	0.9	3.1	3.4	1.3	49.5	210.0	127.0	81.4	39.2	1.5	0.4	2.4	4.2	3.3
1973	-39.46	-1.3					36.5	119.0	99.4	58.0	31.2	-3.4				
1974	-22.02	-0.7					42.9	168.0	132.0	67.9	36.3	-1.6				
1975	52.31	1.7	2.0	7.1	7.8	2.9	32.0	83.8	102.0	58.9	35.1	5.2	2.3	6.9	13.3	8.3
1976	-58.73	-1.9					47.5	97.1	143.0	97.7	71.7	-3.9				
1977	19.27	0.6	0.7	2.6	2.9	1.1	33.1	105.0	65.8	67.5	38.8	1.8	0.7	4.0	4.3	2.8
1978	96.35	3.1	3.6	*13.0*	*14.4*	5.4	39.1	126.0	113.0	58.2	45.8	7.8	2.9	11.5	**24.7**	11.8
1979	74.33	2.4	2.8	*10.0*	*11.1*	4.2	31.8	105.0	87.8	52.1	31.6	7.4	2.6	11.4	**21.3**	**13.2**
1980	53.22	1.7	2.0	7.2	7.9	3.0	38.8	120.0	71.9	44.9	34.5	4.3	1.7	10.0	**17.7**	8.6
1981	103.70	3.3	3.9	*14.0*	*15.5*	5.8	44.9	98.0	144.0	90.1	41.8	7.3	4.0	9.7	**17.2**	13.9
1982	51.39	1.6	1.9	6.9	7.7	2.9	39.3	136.0	104.0	63.1	48.3	4.1	1.4	6.7	12.2	6.0
1983	35.79	1.1	1.3	4.8	5.3	2.0	34.1	98.9	94.6	63.6	32.0	3.3	1.4	5.1	8.4	6.3
1984	53.22	1.7	2.0	7.2	7.9	3.0	33.9	108.0	92.9	66.0	42.9	5.0	1.8	7.7	12.0	6.9
1985	74.33	2.4	2.8	*10.0*	*11.1*	4.2	32.2	87.7	75.3	47.4	38.1	7.3	3.2	13.3	**23.4**	10.9
1986	43.13	1.4	1.6	5.8	6.4	2.4	45.1	186.0	106.0	66.4	36.1	3.0	0.9	5.5	9.7	6.7
1987	56.89	1.8	2.1	7.7	8.5	3.2	33.2	96.1	72.2	49.6	32.6	5.4	2.2	10.6	**17.1**	9.8
1988	90.85	2.9	3.4	*12.3*	*13.6*	5.1	35.5	118.0	81.3	55.3	34.1	8.1	2.9	**15.1**	**24.5**	14.9
1989	54.14	1.7	2.0	7.3	8.1	3.0	37.8	125.0	86.9	77.0	41.8	4.5	1.6	8.4	10.5	7.3
1990	67.91	2.2	2.5	9.2	*10.1*	3.8	44.2	161.0	126.0	67.0	34.3	4.9	1.6	7.3	**15.1**	11.1

Bold = months with over 15% glacier wastage contribution to flow
Shaded areas = years with below 36 cumecs average annual flow at Banff
Italics = months of above 10 cumecs estimated glacier wastage contribution to flow at Banff



Peyto Glacier Mass Balance (Measured 1966-93 & Back-casted 1966-52)

Figs 6.1 and 6.2

Proportions of glacier wastage/discharge for the 5 lowest flow years (%)					
Year	Annual	June	July	August	September
1970	16.8	5.3	28.3	47.4	35.1
1979	7.4	2.6	11.4	21.3	13.2
1975	5.2	2.3	6.9	13.3	8.3
1985	7.3	3.2	13.3	23.4	10.9
1992	6.7	2.4	12.0	21.0	13.2
Proportions of glacier wastage/discharge for the 5 highest glacier volume loss years (%)					
Year	Annual	June	July	August	September
1970	16.8	5.3	28.3	47.4	35.1
1958	9.4	3.6	16.7	29.2	19.6
1961	8.3	2.4	18.3	24.9	20.2
1981	7.3	4.0	9.7	17.2	13.9
1978	7.8	2.9	11.5	24.7	11.8
Proportions of glacier wastage/discharge for the 5 years with the highest ratio (%)					
Year	Annual	June	July	August	September
1970	16.8	5.3	28.3	47.4	35.1
1958	9.4	3.6	16.7	29.2	19.6
1961	8.3	2.4	18.3	24.9	20.2
1988	8.1	2.9	15.1	24.5	14.9
1978	7.8	2.9	11.5	24.7	11.8
Average proportions of glacier wastage/discharge for all 42 years in the study period (%)					
Year	Annual	June	July	August	September
1952-92	2.4	0.8	4.3	7.1	4.7

Table 6.2 Contribution of glacier wastage to flows for selected years

Proportions of Glacier Wastage Contribution to the Flow at Banff for the Month of August (1952-90)

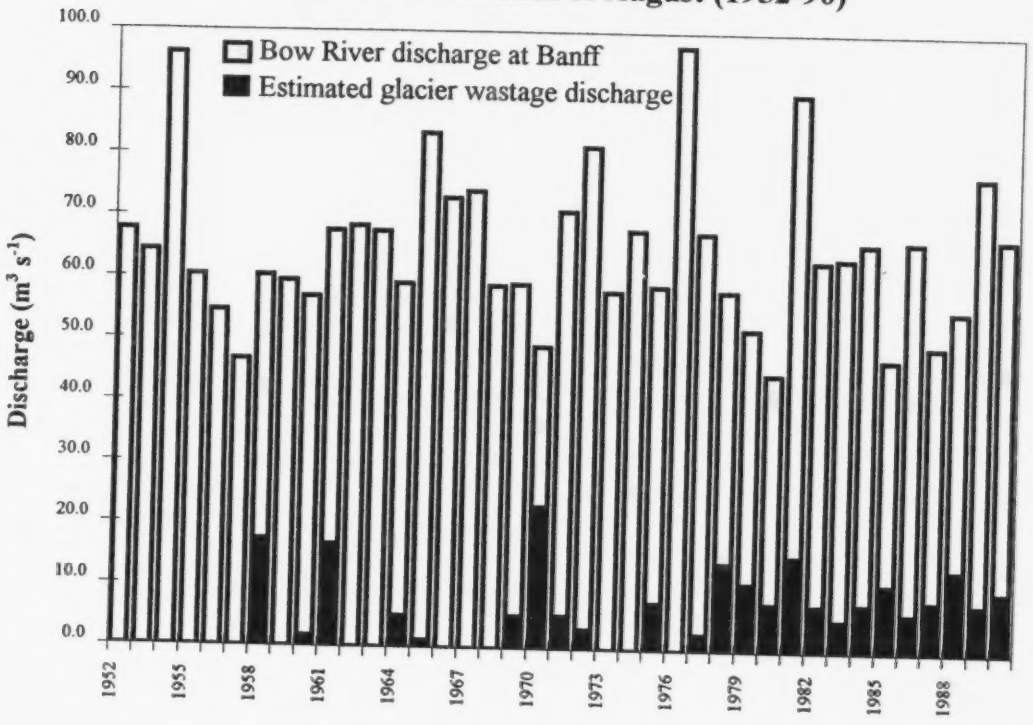


Fig 6.3

7. Conclusions

Main findings of the investigation:

a) For the period 1952 - 92 on average 2.5% of annual streamflow (Bow above Banff) is derived from glacier wastage. On a monthly basis this percentage rises to 4.6%, 7.5% and 5.0% for July, August and September respectively.
b) The years of lowest annual flows are concentrated in the period after 1970. In the 5 lowest flow years the contribution from glacier wastage ranges from 5.2% to 16.8%. For these same years the contribution during August ranges from 13.3% to 47.4%.
c) For the 5 years with the highest contribution of glacier wastage to total flow the proportions range from 7.8% to 16.8%. It is significant that in 1961, a year of *above* average annual flow, 8.3% of that flow was derived from glacier wastage.
d) 1970 stands out as a truly remarkable year, the year of lowest total flow and highest contribution (by far) from glacier wastage.

While some caution is expressed in accepting the precise figures obtained through the analysis, confidence in the general conclusions is high. There is room for improvement in the estimates. Measures to make improvements are already underway.

Sets of air photos are being examined and analysed in much more detail in order to improve the estimation of volumes of glacier wastage over periods of decades. This is the most important additional analysis needed as it is basic to all other calculations. Unfortunately careful analysis of this sort takes some time.

Reconstruction of the record of glacier mass balances (both at the reference glacier, Peyto, and at the suite of glaciers throughout the system) needs more attention and is being undertaken.

At the moment we apply the same monthly apportionment of glacier wastage through the summer period in each year. This is clearly not correct - it may well lead to an underestimation of glacier wastage contributions in some months. However, it probably does not give highly erroneous results as the main concern is the correct inter-annual apportionment of glacier wastage. Again, this aspect is already under additional investigation.

It is clear that the glacier wastage contribution to both annual and to monthly flows is highly significant in many years and especially in those years with already low flows. It will be most worthwhile to continue the investigations with more refined analysis tools and to address various future climatic scenarios.